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小型月面ローバの UWB（Ultra-Wide Band）タグ放出によるランドマーク構築を利用した自己位置推定手法の開発

Development of a Localization Method Using Landmark Construction by Releasing UWB (Ultra-Wide Band) Tag for a Small Lunar Rover

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1. Introduction

In recent years, lunar exploration missions have been planned by governments and private companies around the world, and new technological developments and international competition have been taking place. The development of small lunar exploration rovers has been vigorously promoted for lunar exploration. LEV-1 and LEV-2 rovers were mounted on Smart Lander for Investigating Moon (SLIM). LEV-1 performed leapfrogging on the lunar surface and communication with the ground station[1)], and LEV-2 successfully took photographs of the SLIM after landing on the surface and transmitted the image data[2)]. Carnegie Mellon University, in collaboration with NASA, has developed the 2 kg IRIS Lunar Rover which aims to reach the lunar surface[3)] and Daimon Corporation has released YAOKI, an ultra-compact 2-wheeled lunar rover with a mass of 498 g[4)]. Transporting a large number of these small lunar rovers to the Moon is expected to enable lower-risk and more efficient exploration compared to using a single large rover. Assuming an exploration mission for sample collection and in-situ analysis by multiple small rovers; first, the lander lands near the exploration target, avoiding obstacles. For example, SLIM has a pinpoint landing accuracy of approximately 10 m[5)], and the lander is expected to land dozens of meters from the planned landing site, taking into account obstacle avoidance during landing. Next, multiple rovers disembark from the lander and run dozens of meters to the target exploration site, where the rovers collect samples and perform in-situ analysis and return to the lander with the collected samples. The rovers are expected to run a total of several hundred meters during the above missions.

The functions which are useful for such a mission include the ability to estimate the rover's self-position from the lander and to place landmarks on the lunar surface that have been identified as having absolute positions. If the rover can estimate its own position, it will be possible to achieve reliable sample return and avoid running out of battery power by taking a long detour. In addition, previous research on swarm exploration has reported that it is possible to estimate the relative positions of rovers by measuring the strength of communication between them[6)]. Therefore, it has been suggested that by determining the absolute position of one rover, the absolute positions of the other rovers can also be determined, potentially enabling efficient and safe group exploration. It has been shown that if there are landmarks with known absolute positions on the lunar surface, the rover's self-positioning accuracy can be improved by periodically returning to the landmarks[7)]. Furthermore, the placement of landmarks at a point where the target resource is buried can attract other rovers and improve the exploration efficiency.

Localization methods can be divided into relative localization and absolute localization. Relative localization is a method of continuously adding up relative displacements and has the problem of increasing error accumulation[8)]. Absolute localization has been studied using camera-based terrain matching[9)] and sun sensor-based celestial navigation[10)]; but no research has achieved both low-load processing without using a camera and position estimation accuracy within a few meters. The localization method using communication between multiple landers and rovers[11)] faces the issue of high installation costs for communication bases (landmarks). Additionally, the method that uses communication between four UWB (Ultra-Wide Band) anchors installed on the lunar surface and UWB tags attached to rovers[12)] does not clearly specify the installation method for the communication bases.

Therefore, this study aims to develop a rover which can perform low-load processing and high-precision localization, and which can install landmarks at a low cost. The rover will be equipped with an Ultra-Wide Band (UWB) tag ejection mechanism and a sensor capable of acquiring rover attitude. A method of rover localization will be developed by placing the tag as a landmark on the lunar surface. In this study the rover specifications and the position of the tag ejection to the lunar surface at the time of rover localization are determined, and the accuracy of the rover localization is examined.

2. Development of a Small Lunar Rover and Self-Positioning Methods

2.1. Design of a Small Lunar Rover

Figure 1 shows the specifications of the small lunar rover. The system is controlled by Spresense (Sony), the drive motors are servo motors XM430-W210 (ROBOTIS), and the motor controller is Dynamixel Shield (ROBOTIS). Two UWB anchors will be folded on the top of the rover and will deploy at a distance of 1 m between the anchors when the rover descends from the lander. The rover's attitude will be obtained by measuring the rover's heading angle from the geomagnetic field and angular velocity using the IMU (Inertial Measurement Unit) sensor. It is assumed that the rover's attitude will be measured using a sun sensor to detect the direction of the sun during lunar operations.

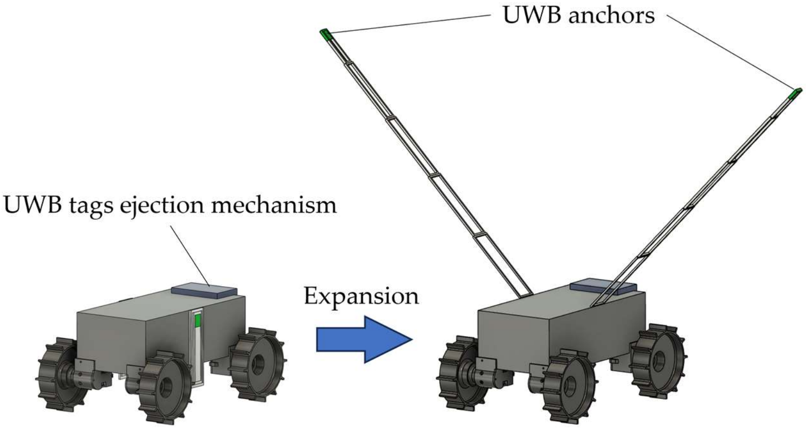


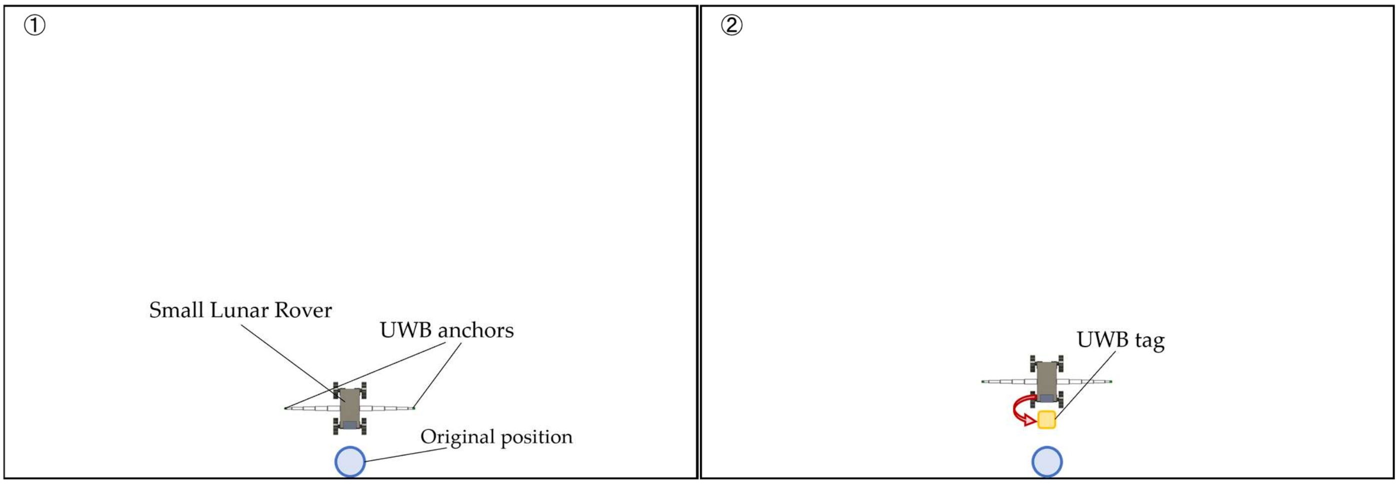
Figure 1. Small Lunar Rover.

2.2. Design of UWB tags and Anchors

UWB wireless communication uses very short pulses and communicates over an ultra-wide frequency bandwidth, resulting in low power consumption and high ranging accuracy[13)]. The UWB anchors (receivers) to be deployed from the side of the rover and the UWB tags (transmitters) to be emitted from the rear of the rover will be manufactured using the UWB modules, DWM1000 (Qorvo).

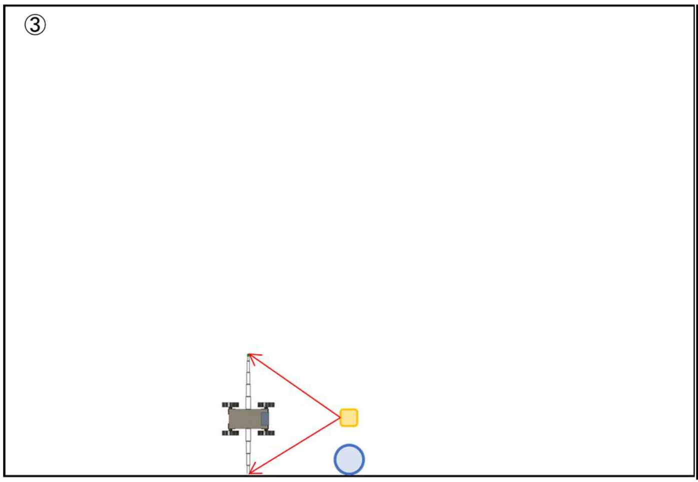
2.3. Operational Sequence on the Lunar Surface

Figure 2 shows the sequence of the rover's localization by tag release on the lunar surface. First, the rover descends from the lander and releases a UWB tag at the landing point of the lander (original position). Subsequently, the rover estimates its position by measuring the distance between the tag and the anchor, as well as by assessing its attitude. Thereafter, it proceeds to move 5 meters in a direction perpendicular to the target point, where it deploys a new tag. The tag position on the lunar surface is determined by measuring the distances between the tags and anchors and the rover attitude. Then the rover begins to run towards the target point, and it continues to determine its position from the two tags during running. As the communication distance between the tags and anchors increases, communication strength decreases and delays occur[14)]. To prevent this, the rover runs in a zigzag manner dropping a tag every 30 m to establish a new communication base and estimate its own position. After the rover arrives at the sample collection point, when the rover's analyzer detects a buried resource, the rover drops the tag on the spot and calls other rovers and efficient sampling operations will be realized. After the rover finishes collecting samples, it returns to the lander while acquiring its own location using the installed tag.

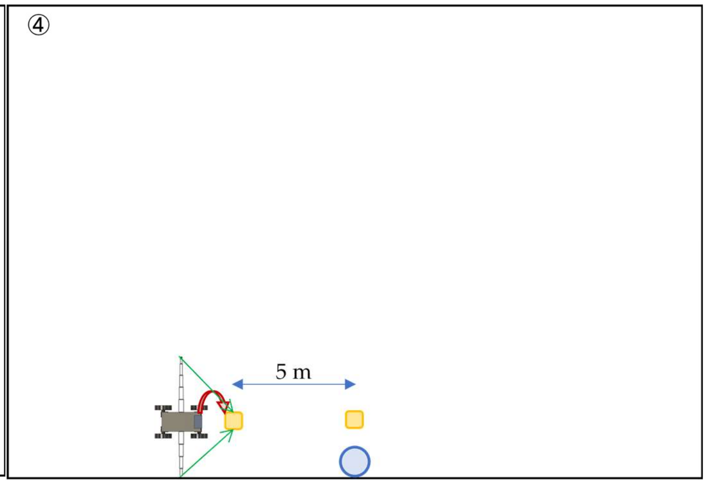


(a) ①Getting off the lander (b) ②Releasing UWB tag

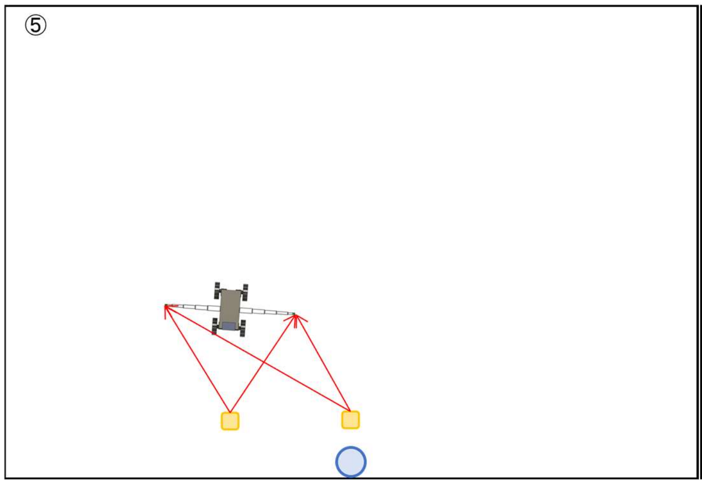
Figure 2. Operating sequence.



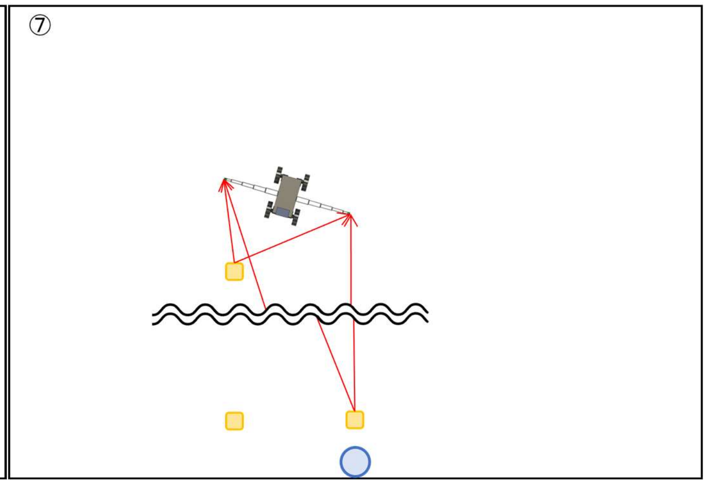
(c) ③Rover localization



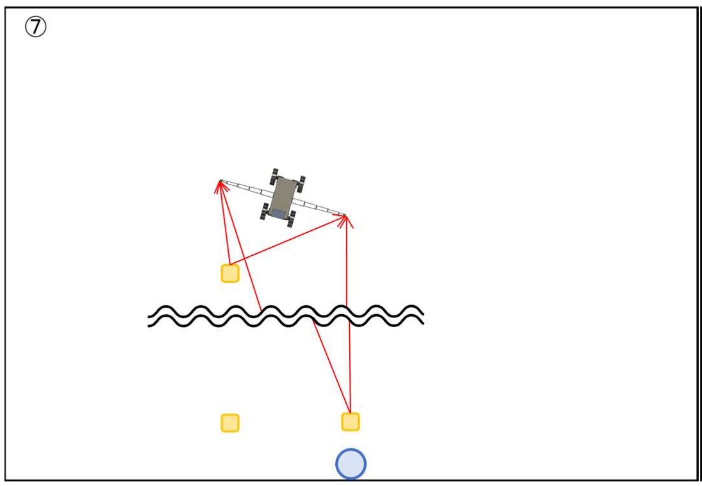
(d) ④Releasing UWB tag and Determining tag localization



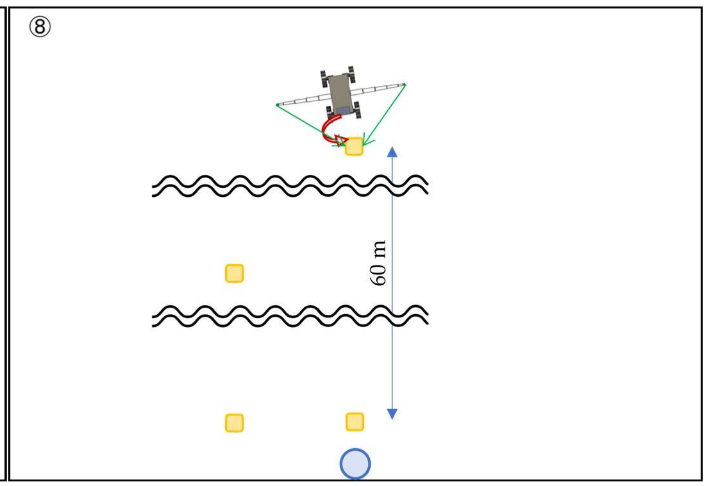
(e) ⑤Rover localization



(f) ⑥Releasing UWB tag and Determining tag localization



(g) ⑦Rover localization



(h) ⑧Releasing UWB tag and Determining tag localization

Figure 2. Operating sequence.

2.4. Field Experiment

In this study, the distance between the tags will be reduced in order to facilitate field experiments in a confined space. First, the rover will drop a tag at the original position (landing point), and then drop a new tag 5 m in the direction perpendicular to the target point. After the rover has determined the tag's position, it begins zigzagging while estimating its own position, and drops three tags every 3 m, which is one-tenth of the distance used in the lunar sequence. The rover makes a U-turn at a point 1 m ahead from the position of the third tag and returns to the original position while acquiring its own position using the installed tags.

2.5. Localization Accuracy

The accuracy of localization using this method was examined. The error in localization during lunar operations was calculated based on a measured distance error of 150 mm, which is specified in the datasheet of the UWB module used, without considering measured errors due to extended communication distance or obstacles. First, the rover estimates its position using the locations of the two tags dropped at the landing site. Figure 3 illustrates the positions of the rover (anchor) and the tags. The yellow and blue lines represent the straight lines connecting the tags and anchors, with the length of each line corresponding to the distance between the tags and anchors. Figure 4 provides an enlarged view of the area around the rover in Figure 3, where the anchors attached to both sides of the rover are depicted as green squares, and the center of the rover is represented by a black circle. Consider the scenario where the rover's true position lies centrally among the three anchor pairs and the three rover center positions depicted in Figure 4. In Figure 4, we consider a scenario where the true positions of the three anchor pairs and the three rover center positions are located at the center. When the measured error in the distance between the tag and the anchor is +150 mm, the estimated anchor position is located 150 mm beyond the extensions of the yellow and blue lines, resulting in the green square at the top of Figure 4, with the rover center position corresponding to the black circle at the top. In this case, the estimated position of the rover is determined to be 149.0 mm in front of the true position, based on the angle and length of the yellow and blue lines (the distance between the tag and anchor). Similarly, when the error is -150 mm, the estimated anchor position is located 150 mm short of the endpoints of the yellow and blue lines, resulting in the green square at the bottom of Figure 4, with the rover center position corresponding to the black circle at the bottom. In this scenario, the estimated position of the rover is determined to be 149.0 mm behind the true position, based on the angle and length of the yellow and blue lines (the distance between the tag and the anchor). Afterward, the rover drops a tag every 30 meters as it zigzags, and its position is determined from the two most recently deployed tags. Figure 5 shows the rover (anchor) position and tag position, while Figure 6 presents an enlarged view of the area around the rover." The estimated position of the rover deviates 149.3 mm from its ground truth position in the forward direction when the measured error is +150 mm and 148.7 mm in the backward direction when the error is -150 mm. Considering that the rover drops the tags three times during the zigzag running, the sum of the accumulated errors in the direction of running is expressed by the following equation.

$$\varepsilon_{m+} = 149.0 + 149.3 \times 3 = 596.9\, mm$$

$$\varepsilon_{m-} = -149.0 + (-148.7) \times 3 = -595.1\, mm$$

Where ε_{m+} is the error in localization at a measured distance error of +150 mm and ε_{m-} is the error in localization at a measured distance error of -150 mm.

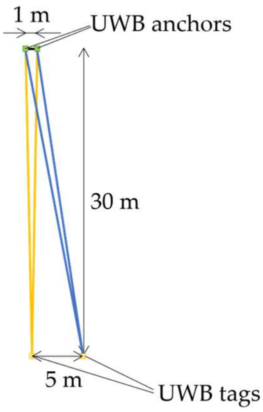


Figure 3. UWB tags and UWB anchors(rover) position at the start of the running when operating on the lunar surface.

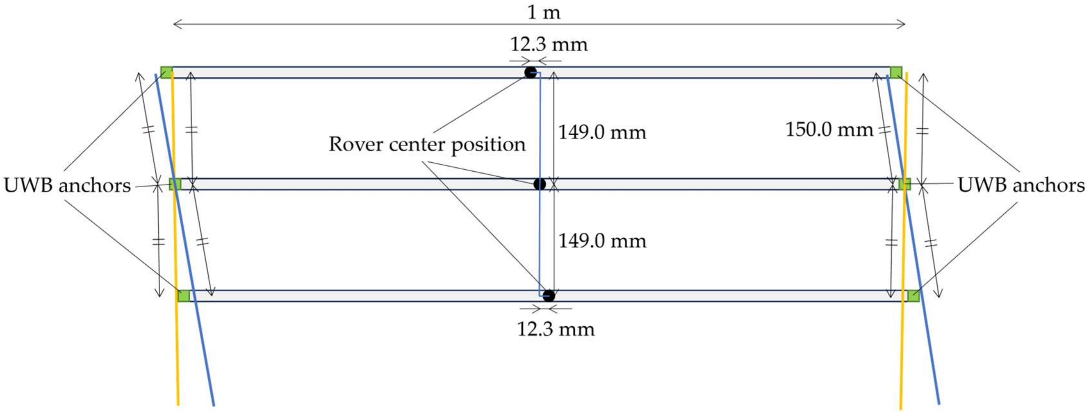


Figure 4. Enlarged view of the anchor in Figure 3.

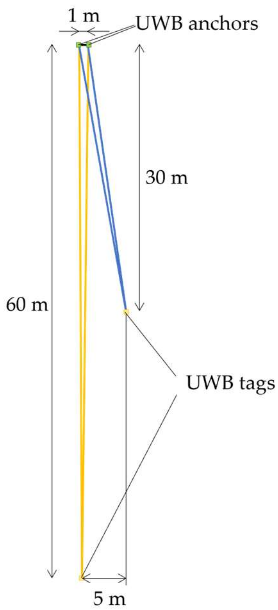


Figure 5. UWB tags and UWB anchors(rover) position at the start of the zigzag running when operating on the lunar surface.

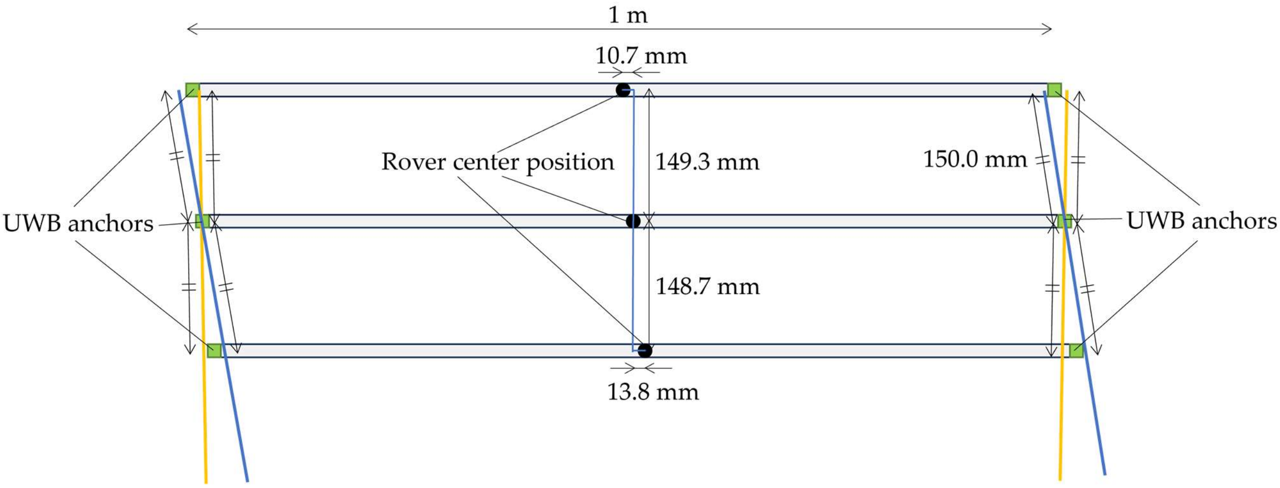


Figure 6. Enlarged view of the anchor in Figure 5.

Next, the error in localization during lunar operations was calculated. The same calculation was conducted by changing the tag drop interval from 30 m to 3 m during zigzag running (Figures 7-10), and the sum of the accumulated errors in the direction of running is expressed by the following equation.

$$\varepsilon_{f+} = 115.6 + 113.5 \times 3 = 456.1\ mm$$

$$\varepsilon_{f-} = -112.4 + (-113.1) \times 3 = -451.7\ mm$$

Where ε_{f+} is the error in localization at a measured distance error of +150 mm and ε_{f-} is the error in localization at a measured distance error of -150 mm.

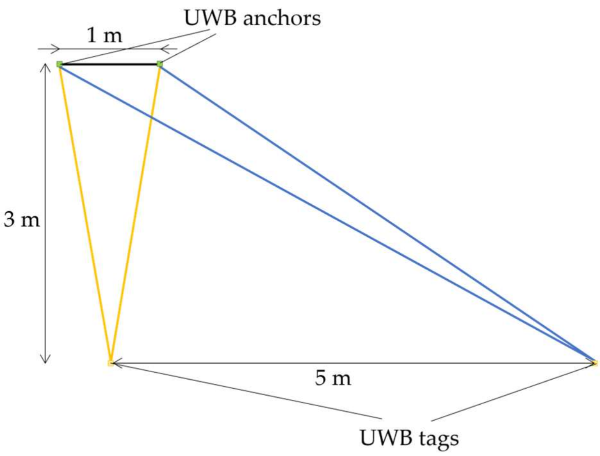


Figure 7. UWB tags and UWB anchors(rover) position at the start of the running in field experiments.

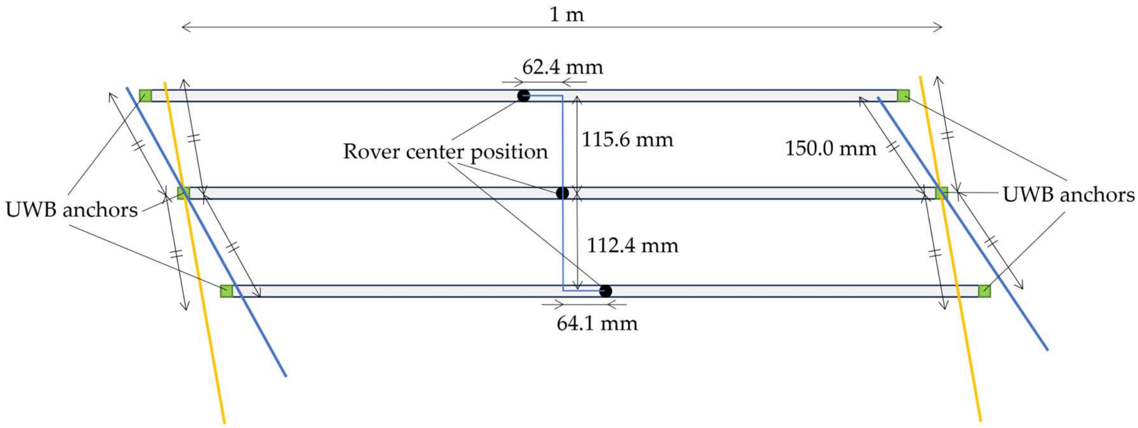


Figure 8. Enlarged view of the anchor in Figure 7.

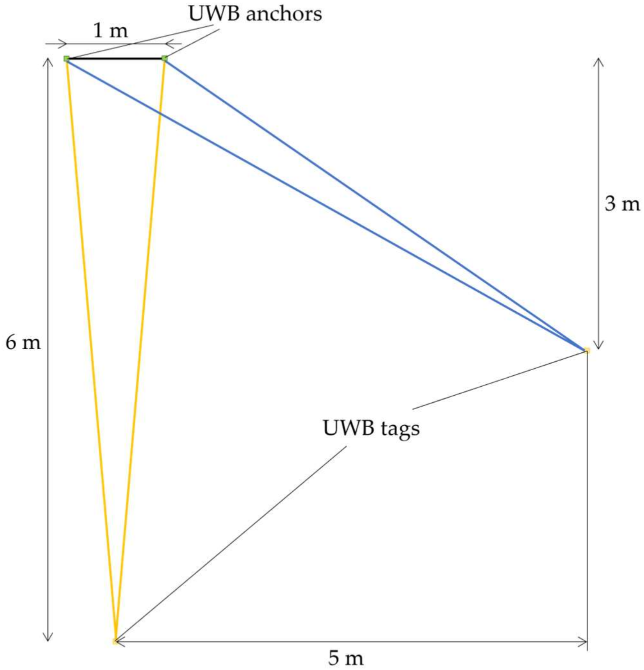


Figure 9. UWB tags and UWB anchors(rover) position at the start of the zigzag running in field experiments.

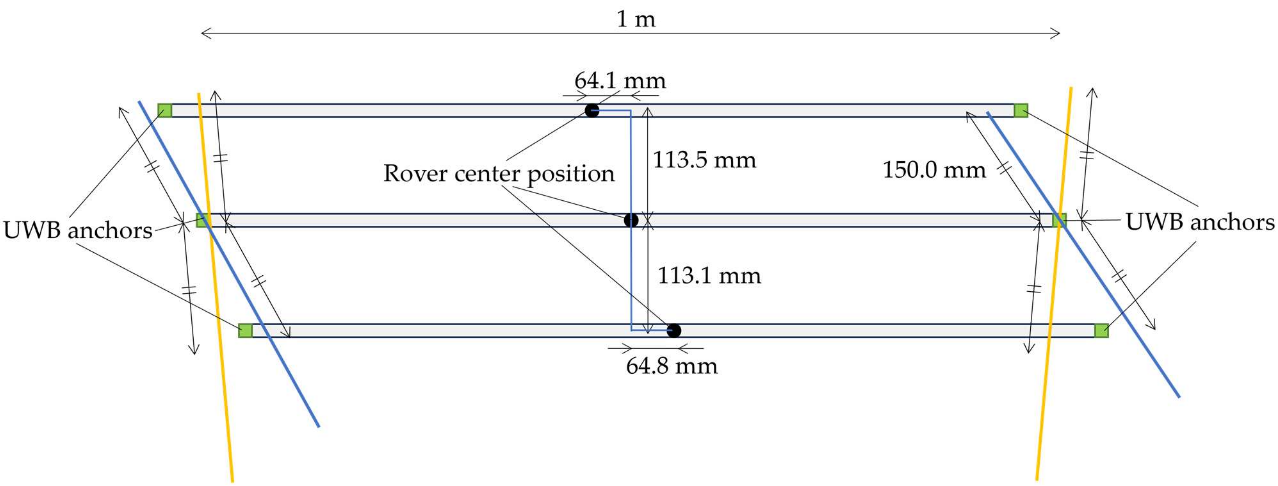


Figure 10. Enlarged view of the anchor in Figure 9.

3. Future Work

In the future, UWB anchors and tags will be manufactured, IMU sensors for attitude acquisition will be calibrated, and these will be mounted on the rover. Field experiment will be conducted, and the obtained accuracy of localization is compared with the accuracy of localization derived from the ranging accuracy of the UWB module to confirm that the theoretical accuracy is obtained. Furthermore, localization is evaluated by triangulation, particle filter, and extended Kalman filter methods, and the true trajectory and the acquired trajectory are compared to determine which method provides the most accurate localization.

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